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Application of Bare Piezoelectric Ceramics in Monitoring Resin Transfer Moulding (RTM) Process

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Abstract

This paper investigates application of piezoelectric ceramics mounted on surface of mould to monitor flow front and curing phases of resin in Resin Transfer Moulding (RTM) process. The piezoelectric ceramic is used for both generating ultrasound and measuring energy of echoed ultrasonic wave at the interface of mould and resin. One of the advantages of this method is that the piezoelectric ceramic can be integrated with electronic circuits in one package, including pulser, signal conditioning, data processing and communication circuits, to make a miniaturized smart sensor. A cost-effective monitoring system can be built by employing the integrated sensors.

An experimental system comprising pulse generation circuitry for driving piezoelectric ceramic and ultrasonic energy measurement circuitry has been built and used in proof of concept experiments. Results of the experiments show effectiveness of bare piezoelectric ceramics in monitoring flow front of resin and curing phases of resin during an RTM process.

Keywords: Piezoelectric, RTM, Ultrasound

1. Introduction

Resin Transfer Moulding (RTM) is a high efficiency and low cost manufacturing method to make large size fibre-reinforced composites components which are of high intensity and light weight. To produce consistent quality moulded products, monitoring and control of resin filling and curing is essential. Conventional methods of monitoring, such as dielectric analysis techniques, direct current conductivity, fibre optic sensors as Fibre Bragg Grating (FBG), fluorescence spectroscopic analysis, require transducer embedded in or in contact with the moulded products, therefore cause either marks on the surface of moulded products or non-reusable sensors. In addition, in a large size moulding system, a great amount of transducers are always required to distribute in grids on the mould. The cost of setup with complex transducers and electronics can be prohibitive.

Ultrasonic methods can provide non-destructive monitoring and convenient setup for a monitoring system. However, conventional ultrasonic methods measuring ultrasonic velocity require costly transducers and precision electronics to build a monitoring system. Furthermore, in RTM with fibre reinforcement, ultrasound has difficulties of transmission into fibre-reinforced resin and extracting an echo signal to measure ultrasonic velocity would be impractical [1, 2].

Bare piezoelectric ceramics are low cost transducers and convenient for installation. Embedding piezoelectric wafer in the mould for monitoring RTM process was researched in [3]. To achieve non-destructive monitoring, direct attachment of piezoelectric ceramics on outer surface of the mould would be preferred. Because of problems of measuring ultrasonic velocity in RTM conditions, piezoelectric ceramics are alternatively used to measure relative energy of ultrasonic echo wave. The piezoelectric ceramics are placed on surface of the mould for generating ultrasound and detecting reflected ultrasonic signal. When an ultrasound arrives at the mould/resin interface nearer to the piezoelectric ceramic, one part of its energy is reflected back to the piezoelectric ceramic while another part is transmitted into resin and is fully absorbed by the fibre-reinforced resin without echo signal from the other side of resin/mould interface. The measured energy (P) can be calculated by integrating squared amplitude of detected echo wave after the piezoelectric ceramic is excited by a pulse,

$$P = \int_0^T y^2(t)dt \qquad (1)$$

where T is the period, y (t) is detected signal by the piezoelectric ceramic.

Application of bare piezoelectric ceramic can substantially reduce size of transducer by integrating a piezoelectric ceramic with electronics including processing and communication circuitry to make a smart sensor. Therefore a RTM monitoring system can be significantly simplified. The integrated sensors can be easily distributed on surface of mould with neat wiring consisting of only power supply and a shielded twisted communication cable.

Prototype circuits for driving piezoelectric ceramic and measuring ultrasonic energy were designed to perform the experiments. The piezoelectric ceramics were attached with epoxy adhesives to the mould surface. The resin flow front and curing was monitored by the experimental setup.

Curves of the measured ultrasonic energy can be interpreted by comparing with traditional parameter ultrasonic velocity. Previous work [4, 5, 6, 7] have demonstrated that rate of change in velocity with respect to cure time is a good measure of the degree of cure, and have shown S-shape of the velocity curve during curing. The measured ultrasonic energy has a correlation with the ultrasonic velocity parameter [2],

$$P = P_{const} + \frac{(\rho_{resin} \cdot v_{resin} - Z_0)^2}{(\rho_{resin} \cdot v_{resin} + Z_0)^2} \cdot P_0 \qquad (2)$$

where P_0 is emitted ultrasonic energy, P_{const} is constant part of measured energy, including pulsed voltage and ultrasound ringing in the transducer, ρ_{resin} is resin density, v_{resin} is ultrasonic velocity, and Z_0 is acoustic impedance of mould.

Curves of relative ultrasonic energy by using bare piezoelectric ceramics are measured in upside down 'S' shape and match good correlation with velocity curve.

2. Sensor circuits

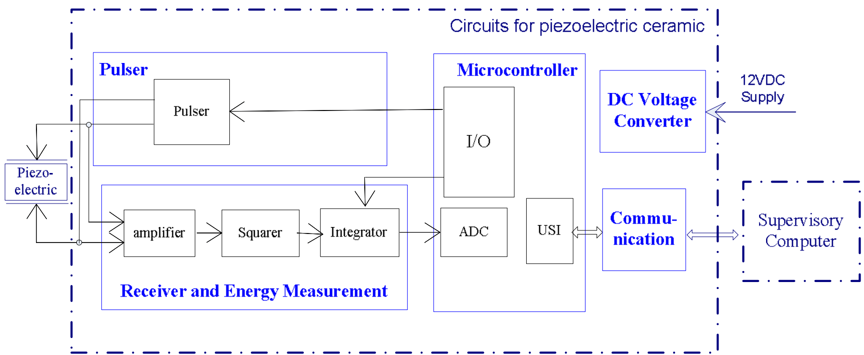


Figure 1. Block diagram of the sensor circuitry

The piezoelectric ceramic is aimed to integrate with its electronic circuits for miniaturizing the ultrasonic sensor. The sensor has autonomic functions of controlling measurement, data collection, and communicating with supervisory computer. The circuits are composed of pulser, receiver, energy calculation, AD conversion, microcontroller, communication interface, and voltage converter, as shown on Figure 1. The potential of integration and convenient wiring in a monitoring system is considered in the design of the circuits. The working voltage is limited within general integrated circuits technology. Besides interfaces with piezoelectric ceramic, the circuitry also interfaces with a single power supply and communication.

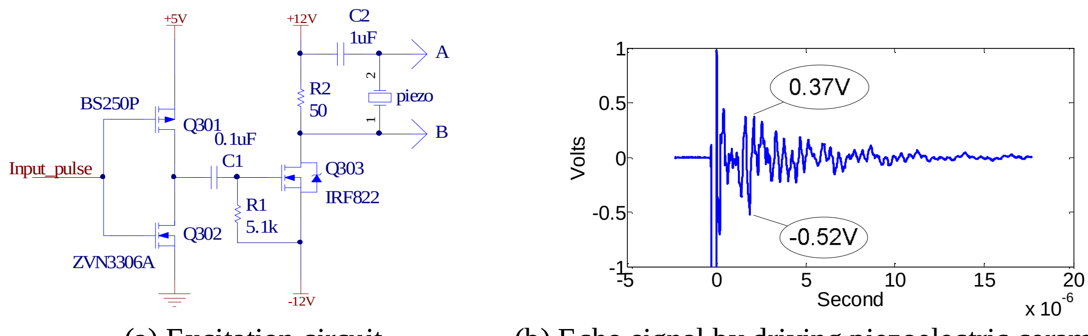
The voltage converter changes the single input voltage 12 Vdc into power supplies for microprocessor (+5V), pulser and signal conditioning circuits (±12V). Atmel micro-controller attiny26 which includes 10-bit AD converters is used for controlling measurement, collecting data, and communication with supervisory computer.

2.1. Excitation of piezoelectric ceramics

The excitation circuit is considered to avoid working in high voltage for easy integration into the sensor. Measurement of ultrasound energy does not depend on high sensitivity and broadband ultrasound and transducers. Compared to sharp pulse which is used in measuring ultrasonic velocity, square pulse can produce much higher ultrasonic energy at the same voltage setting and is used to excite the piezoelectric ceramics to generate ultrasound with lower voltage. When the pulse width is set to half of the wave period of the transducer, the output energy of ultrasound reaches its maximum [8]. For a transducer with centre frequency of 2 MHZ, the pulse width is set to 250ns to acquire maximum output.

The pulser circuit is shown on Figure 2a. It consists of a driving inverter Q302 (N-channel MOSFET ZVN3306A) and Q301 (P-channel MOSFET BS250P), and an N-channel MOSFET Q303 (IRF822). Power supply of the circuit is ±12V which can produce excitation pulse with amplitude about 22V. Input signal of the pulser is generated and controlled by the micro-controller.

When this circuit is used to drive a piezoelectric ceramic PZ27 (6.35 in diameter and 1mm thick with 2 MHZ centre frequency) mounted on a 6mm aluminium mould lid, the measured maximum echo amplitude is -0.52V, as shown on Figure 2b. This is reasonable for inputting to the receiver for amplification and conditioning.



(a) Excitation circuit

(b) Echo signal by driving piezoelectric ceramic mounted on a 6mm-thick aluminium lid

Figure 2. Excitation of piezoelectric ceramics

2.2. Relative ultrasonic energy measurement circuitry

The energy measurement circuits consist of front-end amplifier, squaring and integrator circuits, as shown on Figure 3. Bandwidth of the circuits is 1k-10M Hz fitting for piezoelectric ceramics with centre frequency of 2 MHz.

National Semiconductor high speed LM6171 Op-Amps which offer unity bandwidth of 100MHz and high slew rate of 3600Vms are used for constructing the front-end amplifier U301 and U302, integrator U304, and inverting amplifier U305. The front-end amplifier is connected with differential input and has a gain of 10 and gain bandwidth of 10 MHz. Further gain of 2 is acquired by U302. A 10 MHz bandwidth multiplier AD734 (U303) is used as squaring calculation. The energy integrator is built using Op-Amp U304. Output of the measurement circuits is inverted by U305 to a positive signal for AD conversion.

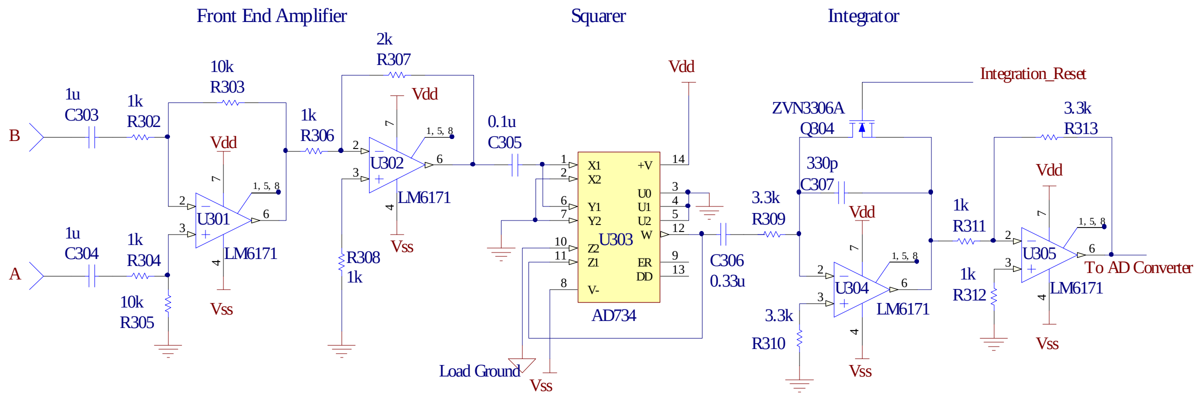


Figure 3. Schematic of receiver and relative ultrasonic energy measurement circuits

Besides energy of useful ultrasonic echo signal, the piezoelectric ceramic also detects constant energy consisting of pulsed voltage applied on the ceramic and ultrasonic wave signal ringing in the ceramic. An n-channel MOSFET Q304 is used as integrator reset switch to control start and reset of integration. As changes of the ultrasonic echo energy is concerned, constant part of the energy detected by the sensor is removed by releasing the switch a short time (2 us, within return flight time transmitting in the 6mm aluminium mould lid) after starting excitation.

3. Experiments and discussion

3.1. Experiment setup

The experiments were carried out using a cylindrical mould with cavity of 70 mm diameter and 10 mm height (Figure 4a). The sealed cylindrical cavity was pre-laid with fibre glass mat. Mixture of resin (Polyester resin, Huntsman AROPOL 1472PLSE) with catalyst (Butanox M50) was injected into the cavity using a syringe. This setup resembles the actual measuring conditions in real moulding process.

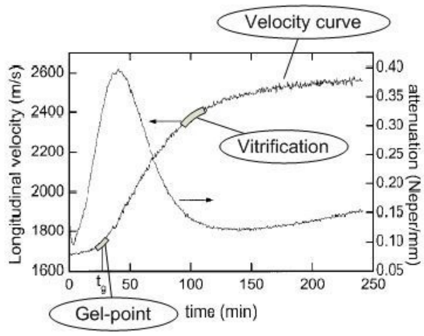
A piezoelectric ceramic PZ27 with 2 MHz centre frequency was mounted on surface of the mould with epoxy adhesive. The established circuits were used for driving the piezoelectric ceramic to generate ultrasound, and measuring reflected ultrasonic echo wave energy. The monitoring system was controlled by a micro-controller which communicated with supervisory computer through RS-485 interface.

3.2. Experiment results

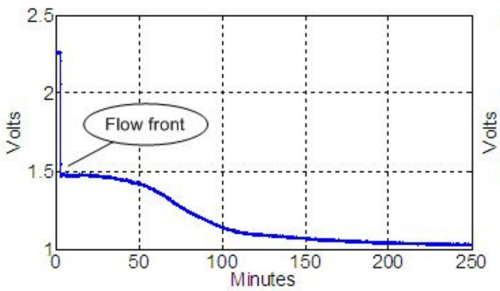
The recorded curve of relative ultrasonic energy in a complete RTM process is expressed in sampled voltage, as shown in Figure 4c. Flow front of resin is indicated by significant energy fall from 2.25 to 1.48 (Volts).

During curing stages, curve of ultrasonic energy wave shows upside down "S" shape (Figure 4d). Gel-point and vitrification are estimated the same way as from ultrasonic velocity curve (Figure 4b). Gel-point is the onset of quick falling of the ultrasonic energy curve compared to onset of quick rising of ultrasonic velocity; vitrification is the inflexion of lower plateau of the ultrasonic energy curve compared to inflexion of high plateau of ultrasonic velocity.

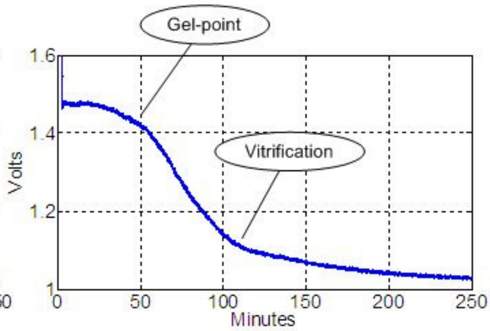
(a) Experiment setup



(b) Referred ultrasonic velocity curve during curing of resin [5]



(c) Result of ultrasonic energy curve measured in the entire RTM process



(d) Magnified vertical axis showing energy movements during curing process

Figure 4. Experiments on monitoring RTM process by using bare piezoelectric ceramic.

4. Conclusion

Experiments with bare piezoelectric ceramic have shown significant change of measured relative ultrasonic energy in indicating resin flow front. The measured ultrasonic energy curve with curing time also showed good correlation with that of ultrasonic velocity. The driving and measuring circuits designed for performing the experiments were relative simple with low working voltage and easy interface for integration, in contrast to complex circuitry required for measuring ultrasonic velocity.

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